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Rock mechanical properties and fracability of continental shale in Zhanhua Sag, Bohai Bay Basin

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Abstract: The rock mechanical properties and fracability of a shale reservoir play an important role in the development of shale oil and gas. There is limited literature on the rock mechanical properties and fracability of continental shale. The mineral composition, compressive strength, Young's modulus and Poisson's ratio of the continental shale in the Shahejie Formation in the Zhanhua Sag were measured by X-ray diffraction and rock mechanical tests under different maturities and confining pressures. The content of carbonate minerals in the shale is the largest, with an average of 44.93%. The content of brittle mineral is slightly higher than that of clay mineral, which is 30.98% and 24.09%, respectively. The failure mode of shale is predominantly splitting under uniaxial compression, which easily forms a fracture network. With additional confining pressure, the failure mode changes to shear mode. The compressive strength, Young's modulus and Poisson's ratio all increase with the rise of confining pressure, but the fracability decreases. The fracability of shale is positively correlated with thermal maturity. By considering mineral composition, mechanical properties, diagenesis and confining pressure, a mathematical model of the fracturing coefficient was established to evaluate the fracability of shale reservoir, which can provide a reference for the selection of fracturing layer.

Keywords: rock mechanics; fracability; continental shale; mathematical model; Zhanhua Sag; Bohai Bay Basin

The shale oil and gas are widely distributed in China, and they exhibit a huge resource potential and constitute one of the important unconventional energy sources [1–4]. Due to the characteristics of shale reservoirs such as self-generating and self-storing, low-porosity and low-permeability, the difficulty of operation is greatly increased, and it requires volumetric fracturing to achieve the purpose of industrial exploitation [5–7]. Shale fracability is proposed to evaluate whether the shale reservoir can be effectively transformed after hydraulic fracturing, and it is an important evaluation parameter in shale oil and gas development [8–9]. For the study of shale fracability, currently there has been no unified evaluation standard yet. Jarvie et al. [10] calculated the shale brittleness according to the quartz content in shale, and considered that the shale with high quartz content would have good fracability; Rickman et al. [11] believed that Young's modulus and Poisson's ratio could reflect the brittleness of shale effectively; Diao [12] combined the mechanical parameters with mineral composition to evaluate the shale's fracability; Fan et al. [13] comprehensively characterized the fracturing potential of shale by taking natural fractures and mechanical properties into account. Since the shale fracability indicates the comprehensive characteristics of shale reservoirs, it is unadvisable to consider the mineral composition or mechanical parameters solely, and the factors such as natural fractures are difficult and costly to quantify, in addition to its high error, so this index cannot be applied effectively.

This paper took the continental shale of the lower section of the 3rd member of Eocene Shahejie Formation in the Zhanhua Sag, Bohai Bay Basin, China as the research object, measured its mineral composition and rock mechanics parameters through laboratory experiments, and combined with the field geological and production data to test the effects of diagenesis and confining pressure on shale brittleness. By considering the four aspects of shale mineral composition, mechanical parameters, diagenesis and confining pressure, the mathematical model for fracability factor was established to provide a new method for the quantitative evaluation of shale fracability.

1 Experimental samples

The mineral compositions of 27 sets of shale samples at different depths of the lower section of the 3rd member of

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Shahejie Formation in Zhanhua Sag were tested, and eight shale samples were selected for rock mechanics experiments. Among them, the samples of Z1h, Z2h, Z3h, Z4h and Z5h were sampled in parallel bedding plane; the samples of Z2-1v, Z2-2v, and Z2-3v were sampled on the vertical bedding plane, and they were sampled at the same depth to Z2h and treated under heat. The fundamental information of the eight samples is shown in Table 1. The organic carbon content (TOC) is 1.54%–5.09%; the vitrinite reflectance (R_o) is 0.56%–0.90%, with an average value of 0.72%; and the thermal evolution degree of organic matter is in the low maturity–mature stage; the organic matter types are mainly type I and type II_1; the porosity is 4.08%–7.04%, with an average value of 5.40%; and the permeability is (4.66–15.05) × 10^{-3} μm^2, with an average value of 6.99 × 10^{-3} μm^2, which belongs to the low-porosity and low-permeability reservoir.

Table 1 Fundamental information of shale samples from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

Sample number	w (TOC)/%	R_o/%	Organic matter type	Porosity/%	Permeability/10^{-3} μm^2
Z1h	3.99	0.56	I	4.99	5.11
Z2h	3.38	0.63	I	4.89	5.64
Z2-1v	3.25	0.71	I	5.07	5.37
Z2-2v	3.31	0.73	I	5.20	4.98
Z2-3v	3.00	0.74	I	5.36	5.79
Z3h	5.09	0.67	I	6.54	9.29
Z4h	1.54	0.80	II_1	4.08	4.66
Z5h	1.59	0.90	II_1	7.04	15.05
Mean value	3.14	0.72		5.40	6.99

2 Experimental method

2.1 X-ray diffraction experiment

The experiment was carried out using the XRDTerra mineral composition tester developed by Innov-X System. The sample was pulverized firstly, sieved through a sieve, and an appropriate amount of powder was poured into a sample tank to carry out the experiment. After the experiment was finished, the obtained spectrum peak was compared with the database card. Then, the mineral component corresponding to each peak was obtained, and the proportion of mineral component was finally calculated.

2.2 Rock mechanics experiment

The experiment was carried out using the MTS816 rock mechanics testing system produced by MTS Company, USA. The maximum vertical press of this system was 1 000 kN; the vertical piston stroke was 100 mm; the maximum confining pressure was 140 MPa; and the maximum heating temperature of the confining pressure chamber was 200 ℃. The shale sample was cut into the standard cylindrical rock samples of φ25 mm × H50 mm, and the upper and lower end faces of sample were smoothed and perpendicular to the central axis. The loading failure under uniaxial and different confining pressures was applied to obtain the stress–strain curve, and the rock mechanics parameters such as compressive strength, Young's modulus and Poisson's ratio were further calculated.

3 Experimental results and analysis

3.1 Whole rock mineral diffraction

3.1.1 The composition of shale minerals

The whole rock mineral composition analysis was carried out on 27 shale samples of the lower section of the 3rd member of Zhanhua Sag. The mineral compositions of different shale are different (Figure 1). The mineral composition of the shale in the lower section of the 3rd member can be divided into three categories, namely brittle minerals, carbonate minerals and clay minerals. The brittle minerals mainly include quartz, feldspar and pyrite. Among them, the contents of quartz and feldspar are large, as 13% and 12.1%, respectively; the content of pyrite is 5.1%. The presence of brittle minerals is beneficial to shale fracability. The carbonate minerals mainly include calcite and dolomite. The calcite is dominant, with an average content of 40.2%; the dolomite content is less, with an average value of 5.4%. The clay minerals mainly include illite, illite-montmorillonite mixed layer, palygorskite, chlorite and kaolinite. Except for kaolinite, the content differences of other components are small. The average content of illite is 8.1%; the average content of illite–montmorillonite mixed layer is 5.9%; the average content of chlorite is 5.8%; and the average content of palygorskite is 4.4%. The clay minerals are mainly characterized by plasticity, and high clay content will not be conducive to fracturing stimulation. The content of carbonate minerals in the study area is the highest, with an average value of 45.6%. The total content of brittle minerals is 30.1%, which is higher than that of clay minerals (24.3%), indicating that the shale in the lower section of the 3rd member exhibits high potential of reservoir transform.

The composition of brittle minerals, carbonate minerals and clay minerals of each sample can be made into a ternary diagram (Figure 2), and four types of lithology, i.e. siliceous shale, calcareous shale, clay shale and mixed shale can be categorized according to the mineral contents. The measured shale samples of the lower section of the 3rd member are dominated by mixed shale and calcareous shale, and most of the mixed shale is biased toward the calcareous shale area. There is only one clay shale, and absent of siliceous shale, indicating the effect of carbonate minerals on shale properties.

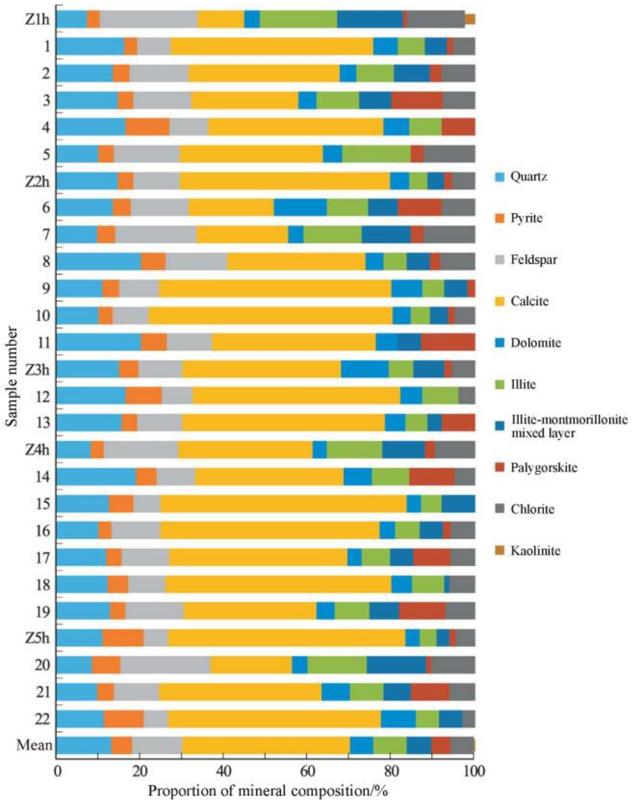


Figure 1 Mineral compositions of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

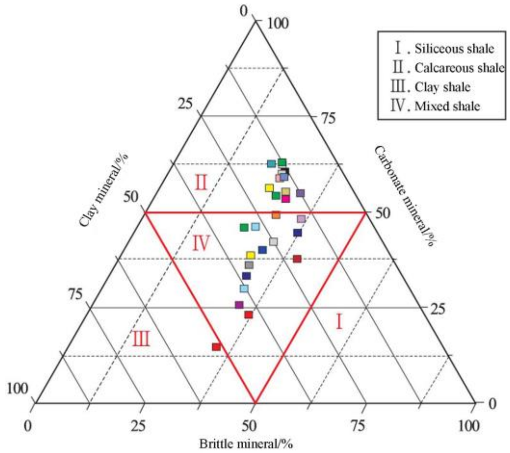


Figure 2 Ternary diagram of mineral compositions of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

3.1.2 Shale mineral composition-based brittleness index

Generally speaking, quartz, feldspar and pyrite are the most important brittle minerals in shale, and their contents largely determine the brittleness and fracability of shale reservoirs [14–18]. However, along with the extensive research of petrophysics and mineralogy, it is found that carbonate minerals can also increase the brittleness of shale [14–15], and the content of carbonate minerals in shale in this study area is high. Therefore, based on the shale mineral composition of the lower section of the 3rd member, the following formula for the brittleness index was obtained:

$$B_1 = \frac{C_b + C_c}{C_t} \quad (1)$$

where B_1 is the shale mineral composition-based brittleness index; C_b is the content of brittle minerals; C_c is the content of carbonate mineral; C_t is total content of minerals; and all the variables are dimensionless.

Figure 3 illustrates that the shale mineral composition-based brittleness index in the lower section of the 3rd member is generally high, and the distribution of brittle minerals in the upper and lower parts is irregular, ranging from 0.49 to 0.88, with an average content of 0.76. This indicates that the shale in the study area has good fracability in terms of mineral composition characteristics.

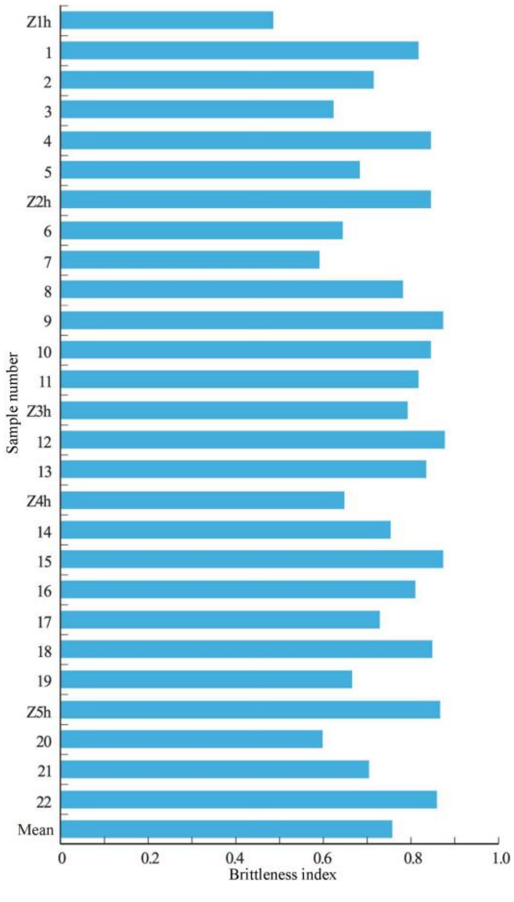


Figure 3 Brittleness index based on mineral compositions of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

3.2 Rock mechanics experiment on shale

3.2.1 Uniaxial mechanics experiment

Figure 4a shows the stress–strain curve in shale uniaxial compression test. This figure illustrates that the shale sample has obvious brittle characteristics under uniaxial compression. In the initial stage, the compaction and concavity phenomenon is not obvious, and it quickly enters the straight line segment, namely the linear elastic deformation stage. The shale mechanical properties are stable in this stage, which are basically not affected after unloading; no obvious plastic characteristics are observed, and the yielding stage is not obvious until the maximum compressive strength is reached and the sample is destroyed; after the peak, the stress declines rapidly.

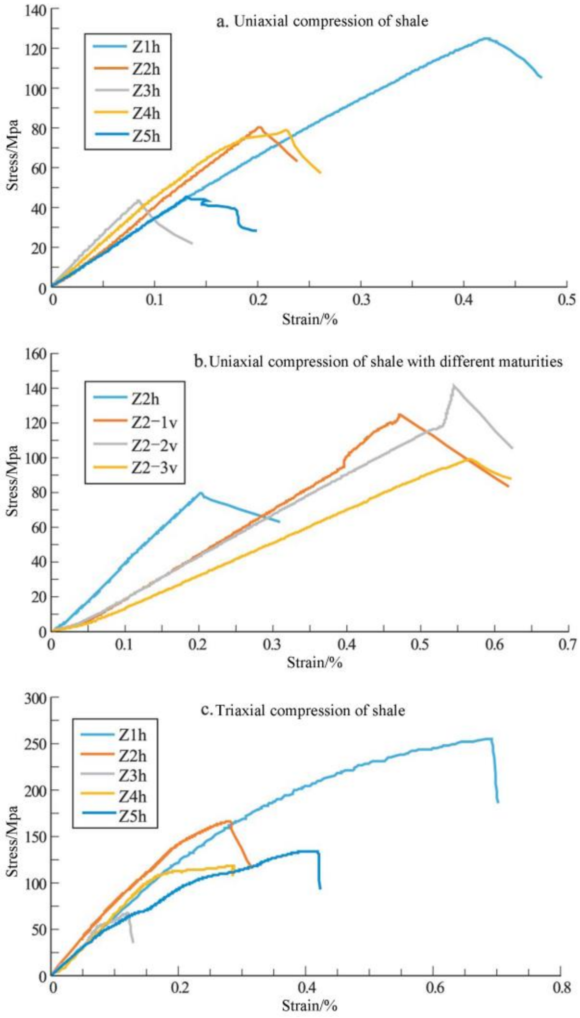


Figure 4 Stress–strain curves of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

The rock mechanics parameters obtained from the uniaxial compression test are shown in Table 2. The compressive strength of the sample ranges from 43.61 MPa to 125.08 MPa, with an average value of 74.55 MPa, which is smaller than that of sandstone or carbonate (about 100 MPa); the Young's modulus is between 34.25 GPa and 53.05 GPa, with an average value of 41.64 GPa; the Poisson's ratio is 0.20–0.33, with an average value of 0.26. According to Sondergeld et al. [19], when the Young's modulus is greater than 24 GPa and the Poisson's ratio is less than 0.25, it is beneficial to forming the fracture network in shale reservoir. The Young's modulus of the shale in the study area is much larger than 24 GPa, and the Poisson's ratio is also close to 0.25, indicating that this interval can be stimulated by volumetric fracturing.

Table 2 Rock mechanical parameters of uniaxial compression of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

Sample number	Compressive strength/MPa	Young's modulus/GPa	Poisson's ratio
Z1h	125.08	34.25	0.22
Z2h	80.30	39.66	0.20
Z3h	43.61	53.05	0.33
Z4h	78.53	46.12	0.29
Z5h	45.22	35.11	0.26
Mean value	74.55	41.64	0.26

3.2.2 Uniaxial mechanics experiment of shale with different maturities

In order to study the influence of diagenesis on the mechanical properties of shale, samples Z2-1v, Z2-2v and Z2-3v cored at the same depth were heated to 321.6 ℃, 336 ℃ and 360.4 ℃, respectively, corresponding to the maturities (R_o) of 0.71%, 0.73% and 0.74%, to obtain the uniaxial compressive stress–strain curve (Figure 4b). Among them, Z2h was sampled parallel to the bedding plane, and Z2-1v, Z2-2v and Z2-3v were sampled perpendicular to the bedding plane. Different from Z2h, the compaction of the other three cylindrical samples is obvious in the initial stage, which may be caused by the pressured closure of the bedding seam; generally, the linear elastic stage is long, the axial strain large, and yield stress point is obvious.

Table 3 shows the uniaxial compression rock mechanics parameters of shale with different maturities. The compressive strength of three sets of samples is between 99.04 MPa and 142.02 MPa, with an average value of 121.99 MPa. It is found that the compressive strength of the vertical sample is generally about twice that of the horizontal sample [20]. The compressive strength of Z2h is 80.30 MPa, which is significantly higher than 1/2 that of the other three sets of vertical samples. The experimental results show that high maturity will reduce the compressive strength. In addition, the Young's modulus and the Poisson's ratio also decrease with the increase in R_o.

Table 3 Rock mechanical parameters of uniaxial compression of shale at different maturities from the lower section of the 3rd member of Shahejia Formation in Zhanhua Sag, Bohai Bay Basin

Sample number	Heating temperature/℃	R_o/%	Compressive strength/MPa	Young's modulus/GPa	Poisson's ratio
Z2h		0.63	80.30	39.66	0.20
Z2-1v	321.6	0.71	124.92	25.25	0.16
Z2-2v	336.0	0.73	142.02	24.46	0.15
Z2-3v	360.4	0.74	99.04	18.95	0.12
Mean value		0.70	111.57	27.08	0.16

3.2.3 Triaxial mechanics experiment of shale

In order to obtain the rock mechanics parameters of the samples under actual formation conditions, the confining pressure was determined to be 40 MPa according to the sampling depth. Figure 4c shows the triaxial compression stress–strain curve of the sample under the confining pressure of 40 MPa. Due to the influence of confining pressure, there is no initial compaction stage. The later part of the curve bends plastically step by step. The yielding section curve is relatively long, and the yield stress point is prominent. Moreover, the strains are quite different when different samples are destroyed.

The rock mechanics parameters (Table 4) of the shale in the lower section of the 3rd member under different confining pressure were tested. Compared with that in the uniaxial mechanical tests (Table 2), the compressive strength in triaxial mechanics experiment is increased from 74.55 MPa to 148.66 MPa, nearly doubled; in addition, from uniaxial compression to the confining pressure of 40 MPa, both the Young's modulus and the Poisson's ratio increase to different degrees, demonstrating the great influence of confining pressure on rock mechanical properties.

Table 4 Rock mechanical parameters of triaxial compression of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

Sample number	Compressive strength/MPa	Young's modulus/GPa	Poisson's ratio
Z1h	254.56	47.89	0.34
Z2h	166.85	77.74	0.41
Z3h	68.05	60.78	0.42
Z4h	118.98	69.94	0.43
Z5h	134.84	58.01	0.43
Mean value	148.66	62.87	0.41

Figure 5 shows that the shale samples are completely different in rupture morphology under the uniaxial and triaxial (40 MPa) compression. According to analysis, due to obvious shale bedding and well-developed micro-cracks, it is easy to break down from the weak bedding planes or micro-cracks during uniaxial compression. The compressive strength is small, and it is prone to cracking from multiple points, which is dominated by splitting failure. After the confining pressure is applied, due to the confining pressure, the bedding or micro-cracks are compacted, and their influence on rock sample failure is reduced. Then, the compressive strength increases, and the rock sample is dominated by shear failure.

3.2.4 Rock mechanics parameters-based brittleness index

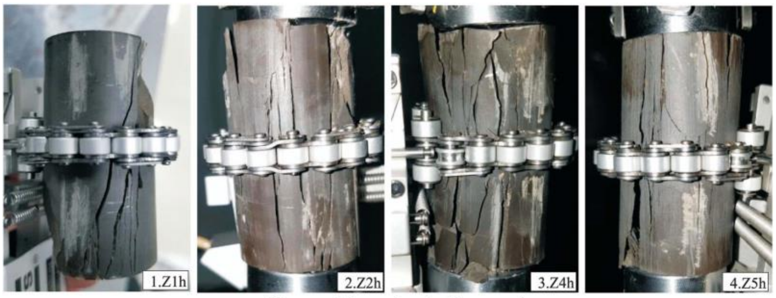
A lot of rock mechanics parameters-based methods can be used to calculate the shale brittleness index, and such methods generally involve in the parameters such as Young's modulus, Poisson's ratio, compressive strength, tensile strength, shear strength and fracture toughness [12,15,21–25]. According to the commonly used elastic parameter method, it is known that the higher Young's modulus can lead to the smaller Poisson's ratio, and then the higher brittleness of shale [11]. Formulas (2)–(4) show the specific calculation.

$$E_{B_2} = \frac{(E - E_{\min})}{(E_{\max} - E_{\min})} \tag{2}$$

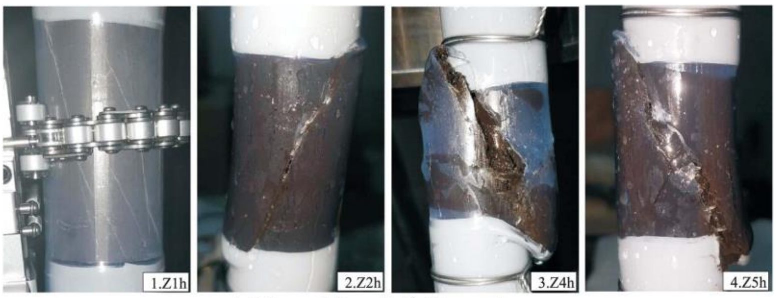
$$\mu_{B_2} = \frac{(\mu_{\max} - \mu)}{(\mu_{\max} - \mu_{\min})} \tag{3}$$

$$B_2 = \frac{(E_{B_2} + \mu_{B_2})}{2} \tag{4}$$

where E_{B2} is the normalized Young's modulus; $E_{\min}$ and $E_{\max}$ are the minimum and maximum of Young's modulus in the study area; μ_{B2} is the normalized Poisson's ratio; $\mu_{\max}$ and $\mu_{\min}$ are the maximum and minimum of Poisson's ratios in the study area; B_2 is the rock mechanics parameters-based brittleness index; and all the variables are dimensionless.

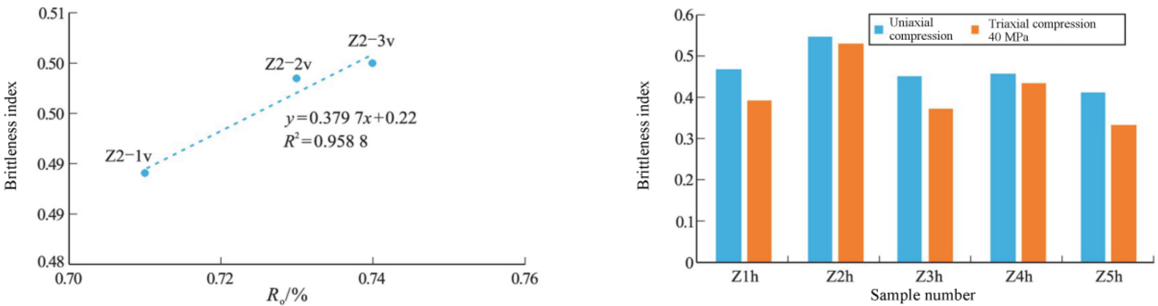


a. Failure morphology under uniaxial compression



b. Failure morphology under triaxial compression

Figure 5 Failure pictures of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin



a. Effect of diagenesis on shale brittleness index

b. Influence of confining pressure on shale brittleness index

Figure 6 Influencing factors of brittleness index of shale from the lower section of the 3rd member of Shahejia Formation in Zhanhua Sag, Bohai Bay Basin

The calculation results are shown in Figure 6. It can be seen from Figure 6a that as R_o increases, the brittleness index of the shale increases accordingly. According to the analysis [8,26], when the value of R_o is low, due to the transformation between clay mineral components, it is prone to the filling of pores and cracks, which is not conducive to fracturing; as the maturity increases, the rock mineral components tend to be more brittle and stable, which further increases the brittleness of shale. In addition, the organic pyrolysis gas production also increases the shale porosity. The shale gas generates pressure inside the shale, which forms micro-cracks. This series of mechanisms promotes the fracability of shale. Figure 6b illustrates that from the uniaxial compression to the triaxial compression (40 MPa confining pressure), different degrees of brittleness index reduction are observed on the shale samples from the lower section of the 3rd member. As seen in Figure 5, since the confining pressure restrains the expansion of micro-cracks, it is difficult to generate multiple fractures, thus lowering the fracability of shale.

4 Evaluation on shale fracability

The fracability evaluation of shale reservoirs involves a lot of factors, including brittle mineral content, rock mechanical properties of shale, diagenesis and natural fractures, and the weight of each factor in the fracability evaluation needs to be studied. However, the diagenesis and natural fractures are difficult to quantify and obviously affected by human factors, so their reference significance is limited. Fracturing is carried out under the actual formation conditions. According to the experimental results, the confining pressure has a significant influence on shale fracability, so it is more advisable to take the confining pressure into account. Therefore, it is necessary to consider the mineral brittleness index, rock mechanics brittleness index, diagenesis and confining pressure of shale comprehensively. Firstly, range transformation method will be used to realize the standardization of each parameter. Then the analytic hierarchy process is used to determine the influence weight of each factor on shale fracability. Finally, the mathematical model for fracability factor can be obtained by linear weighting.

4.1 Parameter standardization

Due to the unique dimension of each factor, it needs to standardize those factors by the range transformation method [26]. According to the experimental results, the influencing factors can be divided into positive indexes, namely the parameters positively related to the fracability, including mineral brittleness index, rock mechanics brittleness index and diagenesis; as well as the negative indexes which mainly include confining pressure, i.e., the parameters negatively related to fracability. The calculation method is shown in Formulas (5) and (6):

Positive indexes

$$S = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (5)$$

Negative indexes

$$S = \frac{X_{\max} - X}{X_{\max} - X_{\min}} \quad (6)$$

where S is the value after parameter standardization; X is the parameter value; $X_{\min}$ is the minimum value of X; $X_{\max}$ is the maximum value of X. After the parameters are standardized, the values are between 0 and 1, no dimension, and it will be better when the value is larger.

4.2 Weights determination with analytic hierarchy process

The influence degree of each factor on the fracability needs to be quantified to accurately evaluate shale fracability. The analytic hierarchy process can be used to determine the weight of each parameter, which divides the problem concerned into several influencing factors, and classifies each factor hierarchically. The factors of each layer are compared in pairs. The relative importance of each factor is determined, and the corresponding scale is given, therefore establishing the matrix to calculate the weight [27–29]. The specific steps are to classify the mineral brittleness index, rock mechanics brittleness index, diagenesis and confining pressure into the same layer, and compare them in pairs based on the SAATY 1-9 scale method [24] to assign the relative importance of each factor and establish the judgment matrix; the value of the judgment matrix can be determined according to the experimental results (Table 5), and then the maximum eigenvalue and eigenvector of the judgment matrix can be solved by the sum-product method, and finally the maximum eigenvalue is used to validate and judge the consistency of the matrix.

Table 5 Judgement matrix of shale from the lower section of the 3rd member of Shahejie Formation in Zhanhua Sag, Bohai Bay Basin

Factor	Mineral brittleness index	Rock mechanics brittleness index	Diagenesis	Confining pressure scale
Mineral brittleness index	1	1/2	3	4
Rock mechanics brittleness index	2	1	5	6
Diagenesis	1/3	1/5	1	2
Confining pressure	1/4	1/6	1/2	1

The eigenvectors of the judgment matrix are obtained as $\boldsymbol{W} = (0.29, 0.52, 0.12, 0.07)$, namely that the weights of mineral brittleness index, rock mechanics brittleness index, diagenesis and confining pressure in the mathematical model of fracability evaluation are 0.29, 0.52, 0.12 and 0.07, respectively. The consistency check coefficient of the judgment matrix is 0.013 (0.013 < 0.1), which meets the consistency requirement.

4.3 Fracability coefficient mathematical model

According to the weight of each influencing factor obtained by the analytic hierarchy process, the formula for fracability coefficient calculation was obtained by weighting:

$$F = 0.29B_1 + 0.52B_2 + 0.12D + 0.07C \tag{7}$$

where F is the shale fracability coefficient; B_1 is the standardized mineral brittleness index; B_2 is the standardized rock mechanics brittleness index; D is diagenesis, with standardized R_o value as the parameter; C is the standardized confining pressure value; and all the factors are dimensionless.

The fracability of shale in the lower section of the 3rd member in Zhanhua Sag was evaluated by the mathematical model of shale fracability coefficient. According to the calculation results, the fracability coefficients of Z1h, Z2h, Z3h, Z4h and Z5h are 0.290, 0.853, 0.445, 0.396 and 0.410, respectively. The shale fracability coefficient of the lower section of the 3rd member is between 0.290 and 0.853, with an average value of 0.479. The fracabilities of each layer are quite different, and the fracability coefficient of the Z2h sample is the largest, which is 0.853. From the viewpoint of fracability, it can be selected as the fracturing layer.

5 Conclusions

(1) The largest content of shale in the lower section of the 3rd member in Zhanhua Sag is carbonate minerals, with an average content of 44.93%; followed by that of brittle minerals, which is 30.98%; and finally that of the clay minerals, with an average content of 24.09%. Mixed shale and calcareous shale are dominant, and the mineral composition of this area is favorable for shale fracturing.

(2) In the uniaxial mechanics experiment, the compressive strength of the shale in the lower section of the 3rd member is smaller than that of the sandstone or carbonate rock, with an average value of 74.55 MPa, and the average values of Young’s modulus and Poisson’s ratio are 41.64 GPa and 0.26, respectively. The failure is dominated by splitting with multi-cracks; the compressive strength, Young’s modulus and Poisson’s ratio increase after the confining pressure is applied, exhibiting the shear failure and reduced fracability; along with the increase in thermal maturity, the compressive strength, Young’s modulus and Poisson’s ratio of shale are all reduced, and the fracability is enhanced.

(3) By combining the experimental results with the actual geological conditions, and taking the mineral brittleness index, rock mechanics brittleness index, diagenesis and confining pressure of shale into account, the weights of above factors on shale fracability were determined to be 0.29, 0.52, 0.12, and 0.07 respectively by using the analytic hierarchy process. The mathematical model of shale fracability coefficient was established based on the above result, and the average fracability coefficient of shale in the lower section of the 3rd member was calculated to be 0.479. There are certain differences in different horizons, and fracturing can only be conducted on the selected layer.

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